I-Xe DATING OF CHONDRULES FROM THE QINGZHEN UNEQUILIBRATED ENSTATITE CHONDRITE.

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Introduction: Enstatite chondrites sampled a uniquely reduced part of the solar system which is believed to have had a higher C/O ratio than that of the nominal canonical solar system. Whether this difference is due to temporal or spatial variations remains unclear. In an attempt to clarify the relationship between the enstatite chondrites and their more oxidised counterparts we have undertaken I-Xe dating of individual chondrules from one of the most primitive known enstatite chondrites, Qingzhen (EH3). These have been compared with the standards, Bjurbole and Shallowater to enable comparisons with ages previously obtained for chondrules from primitive ordinary chondrites. Furthermore the comparison of the enstatite chondrites with the aubrite Shallowater may help us to understand possible evolution of the reduced region of the nebula.

Many primitive ordinary chondrites show signs of hydrous alteration. This has always presented problems in the interpretation of I-Xe ages in these meteorites as the metasomatising fluids are believed to be halogen-rich [1]. Iodine may have been introduced during this alteration phase so whether I-Xe dates nebular or parent body processes is not clearly understood. Enstatite chondrites appear to offer a simpler picture as there are no reports of hydrated minerals and the presence of extremely soluble primary (*i.e.* igneous or nebula condensates) sulphides, such as oldhamite (CaS), in chondrules and matrix attests that aqueous fluids cannot have played a significant role in the evolution of the enstatite chondrites. Hence the I-Xe ages may reflect a non-aqueous process.

Unmetamorphosed enstatite chondrites are less common than ordinary chondrites of equivalent petrologic type and were subject to higher temperatures than those experienced by their ordinary chondrite counterparts. Estimates for type E3 metamorphic temperatures are less than 600°C [2, 3] but presence of glassy mesostasis in chondrules [4] attests to the unaltered state of at least some of the chondrules in these meteorites. Reports of high halogen contents (in excess of 2.2% Cl [5]) of these glasses leads us to believe that they may contain iodine and that this may have recorded chondrule formation ages.

Qingzhen is amongst the most primitive of the enstatite chondrites and is one of only two E3 falls. The other, Parsa, shows signs of terrestrial alteration [5] which may compromise its usefulness for dating. Antarctic samples (*e.g.* Y6901), even those which are apparently unaltered, may give anomalously young ages due to iodine contamination from the ice (*e.g.* [6]).

Unfortunately there is evidence that Qingzhen is not entirely pristine. Rb-Sr, K-Ar and Ar-Ar dating all imply that there was an episode of isotopic re-setting for Qingzhen between 1.4 and 2.8Ga which has been attributed to shock or to metamorphic or hydrothermal reactions leading to the decomposition of K-bearing and Rb-bearing phases [7, 8].

Analytical: Chondrules were separated from Qingzhen and cleaved into two or more pieces. The largest fraction was irradiated for I-Xe dating using the RELAX mass spectrometer [9] and the rest used for petrographic and mineralogical characterisation.

Results: The selected chondrules have sampled most textures previously described from Qingzhen, (porphyritic pyroxene (PP), porphyritic olivine/pyroxene, radial pyroxene (POP/RP), crypto-crystalline (CC) and barred pyroxene (BP) [in which olivine bars are overgrown by barred pyroxene - 5]) with the exception of the rare forsterite chondrules and Ca,Al-rich chondrules [4]. However the small number studied means that they are not representative of the actual abundances present in the meteorite (see Table 1).

All the Qingzhen chondrules show the typical reduced mineralogy of ECs and none contain more than 20% olivine. Although the mesostasis appears glassy the presence of crystalites cannot be entirely discounted and there is some evidence that Qingzhen chondrules may have started to devitrify [5]. Compositions for the interstitial glasses range from sodalitic, which are highly enriched in chlorine, to albitic with variable amounts of K and Ca.

The iodine contents range over a factor of 3, but there is no clear correlation with either textural features or mineralogy. However there may be a weak anti-correlation between iodine content and chondrule size but by the nature of such a small sample size such a correlation is extremely tentative.

Most chondrules give excellent isochrons. Only one of the chondrules (QC1) shows evidence for a slight isotopic disturbance, but the error is still less than 1Myr.

All but one of the I-Xe ages are younger than the Shallowater standard, with the single exception (QC4) predating Shallowater by 1.08 Myr. The average age for the chondrules in Qingzhen is +0.74 Myr after Shallowater (+1.02 Myr after Bjurbole). This 3Myr range in ages is greater than the age errors, hence appears to be real, and lies between the previously measured ages for whole rock EH and EL chondrites [10].

As has been observed in other meteorites there is no apparent correlation between chondrule textures, mineralogy, iodine content and their ages.

Discussion: *Comparisons with other meteorites.* The carriers of iodine in the aubrites and other reduced achondrites has been shown to be enstatite, thereby indicating that the ages reflect the closure of enstatite during cooling giving an igneous age [11]. In the metamorphosed ordinary chondrites the carriers of iodine are metamorphic minerals, phosphate and feldspar, thereby reflecting the closure age of these minerals during the parent body cooling [12]. Similarly in the primitive achondrites (acapulcoites, lodranites) the carriers are phosphates and feldspar but are believed to be recording an igneous closure age [13].

Unlike the higher grade meteorites the iodine carriers in the unequilibrated, unmetamorphosed chondrites are largely unknown. In some cases high iodine abundances are found in sodalite-rich inclusions, but the origins of this type of inclusion are unclear and the majority of the iodine in the meteorite whole rock is probably not carried by this mineral. Whether the iodine present is due to primary events or secondary processes is not clear.

The so called “Qingzhen reaction” leading to the partial breakdown of some of the more soluble sulphides [14, 15] in a process which supposedly occurred only 1.4 Ga [16] has clearly not affected the I-Xe ages. Had there been any effect we would expect to see highly disturbed isochrons or no evidence for correlated $^{128}Xe^*/^{129}Xe^*$.

The I-Xe ages derived for the Qingzhen lie within the range of chondrules from Allende, Semarkona and Parnallee [17, 18, 19] but have a slightly more limited range (3Myr and *ca.* 8Myr respectively). Ages for the latter meteorites have been variously ascribed to hydrothermal processes. However the enstatite chondrites have not experienced the same degree of hydrothermal alteration, but contain at least as much iodine as the more aqueously altered ordinary chondrites. Since metamorphic temperatures appear insufficient to crystallise the chondrule glasses, assuming that the devitrification temperatures are lower than the Xe closure temperature of the glass, metamorphic ages also appear unlikely. Hence it is difficult to understand these ages in terms of anything but primary crystallisation. As such our preferred interpretation of the ages in the Qingzhen chondrules is that they are primary chondrule crystallisation ages.

Comparisons with Shallowater: Previous studies of the Shallowater meteorite have concluded that it was formed by the collision of a molten impactor with a solid planetessimal in the “enstatite chondrite region” of the nebula [20]. So if the chondrule I-Xe ages are actual crystallisation ages of the chondrules then it is apparent that the evolution of bodies in this area was extremely complex as the collision of planetessimal sized bodies was co-eval with chondrule formation.

The I-Xe ages span a range of 3Myr, from 1Myr before Shallowater to 2Myr after Shallowater closure (Shallowater closure occurred 0.28 Myr after that of Bjurbole [21]). The major iodine carrier in Shallowater has been shown to be enstatite and the I-Xe age interpreted as the crystallisation age for this mineral, thereby dating the impact event which formed the meteorite [11].

Conclusions: (1) For Qingzhen the I-Xe chronometer is decoupled from and more stable than both Ar-Ar and Rb-Sr chronometers which were reset by unknown processes between 1.4-2.8 Ga.

(2) The range in I-Xe ages obtained for Qingzhen chondrules are comparable to those observed in most unequilibrated ordinary chondrite chondrules. Hence the enstatite chondrite region of the nebula was undergoing the same processes (*i.e.* I-Xe closure of chondrules) at the same time as the more oxidised regions of the nebula. This suggests a spatial rather than temporal control of the reduced region of the nebula.

(3) Whilst it has been argued that the I-Xe ages derived for chondrules from the unequilibrated ordinary chondrites are those of a secondary process, such as aqueous alteration introducing the halogens, there is little evidence for such a process in the enstatite chondrites. Indeed the presence of such soluble minerals as oldhamite argues strongly against the passage of hydrous fluids.

From this it is tempting to suggest that the observed ages in the unequilibrated enstatite chondrites are primary and, by implication, perhaps also those of other unequilibrated chondrites (see conclusion 2).

(4) Previous studies have suggested a hiatus between the I-Xe ages of the EH (*ca.* 1 Myr before Bjurbole) and EL (*ca.* 3 Myr after Bjurbole) chondrites [10]. The data derived for the individual Qingzhen chondrules span the range between these meteorites but suggests an age closer to that of the EL chondrites than the EH. The differences of chondrule ages and whole-rock ages may be due to the presence of matrix in the latter.

(5) That the chondrule ages overlap the age of Shallowater attests to the rapid evolution of the region of the nebula producing the reduced meteorite parent bodies.

Table 1. Characteristics of Qingzhen Chondrules

Sample	Wt (mg)	Texture	Age (Myr)*
QC1	2.18	BP	+1.98
QC2	0.57	POP	
QC3	1.28	RP	+0.44
QC4	0.74	CC	-1.08
QC5	0.17		+1.41
QC6	3.79	CC	+0.10
QC7	0.72	POP	+0.64
QC8	7.72	POP/RP	+1.70

*All ages are relative to Shallowater (+0.28Myr after Bjurbole - [21]) assuming a half-life for ^{129}I of 16Myr

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